Chapter

Novel Trend in the Use of *Opuntia* (Cactaceae) Fibers as Potential Feedstock for Material Science Applications

Faten Mannai, Ramzi Khiari and Younes Moussaoui

Abstract

Lignocellulosic fibers from *Opuntia* biomass, family Cactaceae, were mainly studied for their sustainability and cellulose content richness. This chapter highlights the current exploitation of *Opuntia* (Cactaceae) as potential feedstock for value-added applications such as reinforcement in composites and paper manufacturing. Cellulosic fibrous network fractions were isolated from different plant parts, and their fundamental properties, chemical and structural compositions, were analyzed, and the obtained results were discussed. The obtained fibrous networks were incorporated into two thermoplastic polymers; their enhancement properties and biodegradability have been studied. However, different recent methods of cellulose fiber extractions (pulping) and paper manufacturing have been investigated by testing two procedures of delignification: chemical and semichemical pulping process; these operations were followed by fibrous suspension characterizations and paper productions. The obtained results show the suitability of *Opuntia* (Cactaceae) for the new trend in ecological and green materials.

Keywords: *Opuntia*, fibrous networks, chemical composition, composites, pulping

1. Introduction

Opuntia (Cactaceae) is a cactus (non-forest and perennial plant) from tropical, subtropical, arid, and semiarid regions, which exists in the form of a shrub or a tree and has an original-look/unique morphology with a height of up to 5 m and produces a sturdy trunk as it ages [1, 2]. This particular species exhibits extraordinary water storage capacity and is known for their drought-tolerant characteristics (xerophytic) [1, 3]. A wide variety of this species and subspecies has been developed, distinguished by spiny or spineless cladodes, cladode shape, branching, fruit color, pulp color, epicuticle wax morphology, and many other properties [4–7]. Cactaceae is a great tree-like cactus formed by numerous up-flat branches (cladodes) [8, 9]. In branches, cellulosic fibrous tissues are slowly grown and arranged in parallel and fuse laterally with neighboring ones, forming a flat net-like structure [10], strongly similar to the cellular structure of *Luffa cylindrical* fibers [9]. This natural cellular structure is made up of an interconnected network of fibers struts, which form the edges (angle situated between two struts) and faces of cells, and possesses excellent mechanical behaviors in spite of its low density [11]. Their specific mechanical properties are due to the hierarchical composite organization [12, 13]. Cactaceae is mainly considered as a rich plant of natural food mineral, protein, vitamin, dietary fiber, and antioxidant compound which can represent an important product to prevent some health problems, such as diabetes, cancer, cataracts, macular degeneration, and neurological and cardiovascular diseases [7, 14–18]. The fruit syrup of *Opuntia* has a powerful antioxidant effect and exhibited effective antimicrobial activity against *Staphylococcus aureus* and *Staphylococcus epidermidis* [19]. Indeed, Cactaceae by product (cladodes, fruit peels, seeds, etc.) was used for non-food applications by testing their applicability to decontaminate wastewater through both the adsorption and coagulation–flocculation processes [8, 20]. It also will be a valuable resource for new applications and devoted to the future trends in terms of applications of natural fibers in different sectors. Furthermore, it is considered as one of the strongest and stiffest available lignocellulose fiber from renewable plant biomass [8, 20, 21]. Recently, the developing needs for new alternative green-based product have led to enlarge the discovery and the research of new renewable resources of natural fibers. This chapter addresses this research and gives an overview of potential exploitations of a new renewable non-woody lignocellulose source from plant biomass which is *Opuntia* (Cactaceae). It is interesting to point out there are only very few reports on the use of *Opuntia* fibers as raw material for paper manufacturing and as natural filler in reinforced polymer composite sectors, and they have been found to be the most interesting and discerning materials.

The pulp and paper industry, one of the largest and diversified industrial sectors in the world, produced every year more than 400 million tons of paper by different manufacturing methods using wood raw materials [22] and many types of non-wood raw materials such as bagasse (sugarcane fibers), cereal straw, bamboo, reeds, esparto grass, jute, flax, and sisal [23]. For this reason, the selection of suitable non-wood fibers is critical for the yield of fibrous fraction, ease of processing, quality, and cost of the final fiber-based product [24]. *Opuntia* (Cactaceae) was used for paper manufacturing as non-woody fibers by applying two different pulping processes. The first procedure is based on the utilization of semi-chemical treatment using a soft operation of chemical delignification in soda-hydrogen peroxide (soda-HP) mixture and mechanical grinding for fiber deliberation [25]. The second procedure is a chemical treatment with soda-anthraquinone mixture (soda-AQ) [26].

The development of fiber-reinforced composite material as an alternative over many conventional materials has been characterized by their eco-friendliness regarding the accumulation of plastic waste in the environment, durability, and its significant enhancement in the structural, mechanical, and tribological properties [27–30]. The natural fiber-reinforced polymer composites (FRPCs) were used to replace conventional metal/material and synthetic fiber/material in various applications in order to reduce weight and for energy conservation. Different kinds of natural fibers are mainly used for developing natural FRPCs with high specific properties, cost effectiveness, and renewability. Plant fibers include leaf fibers (sisal and abaca), bast fibers (flax, jute, hemp, ramie, and kenaf), grass and reed fibers (rice husk), core fibers (hemp, jute, and kenaf), seed fibers (cotton, kapok, and coir), and all other types, which may include wood and roots [31]. FRPCs are also classified according to their content, i.e., based polymeric material and the filler one. The based polymer, which binds or holds the filler material in structures, is termed as a matrix or a binder material, while the filler material is present in the form of sheets, fragments, particles, bundle, or whiskers of natural fiber [31]. Fibers can be placed unidirectionally or bidirectionally in the specific orientation into the

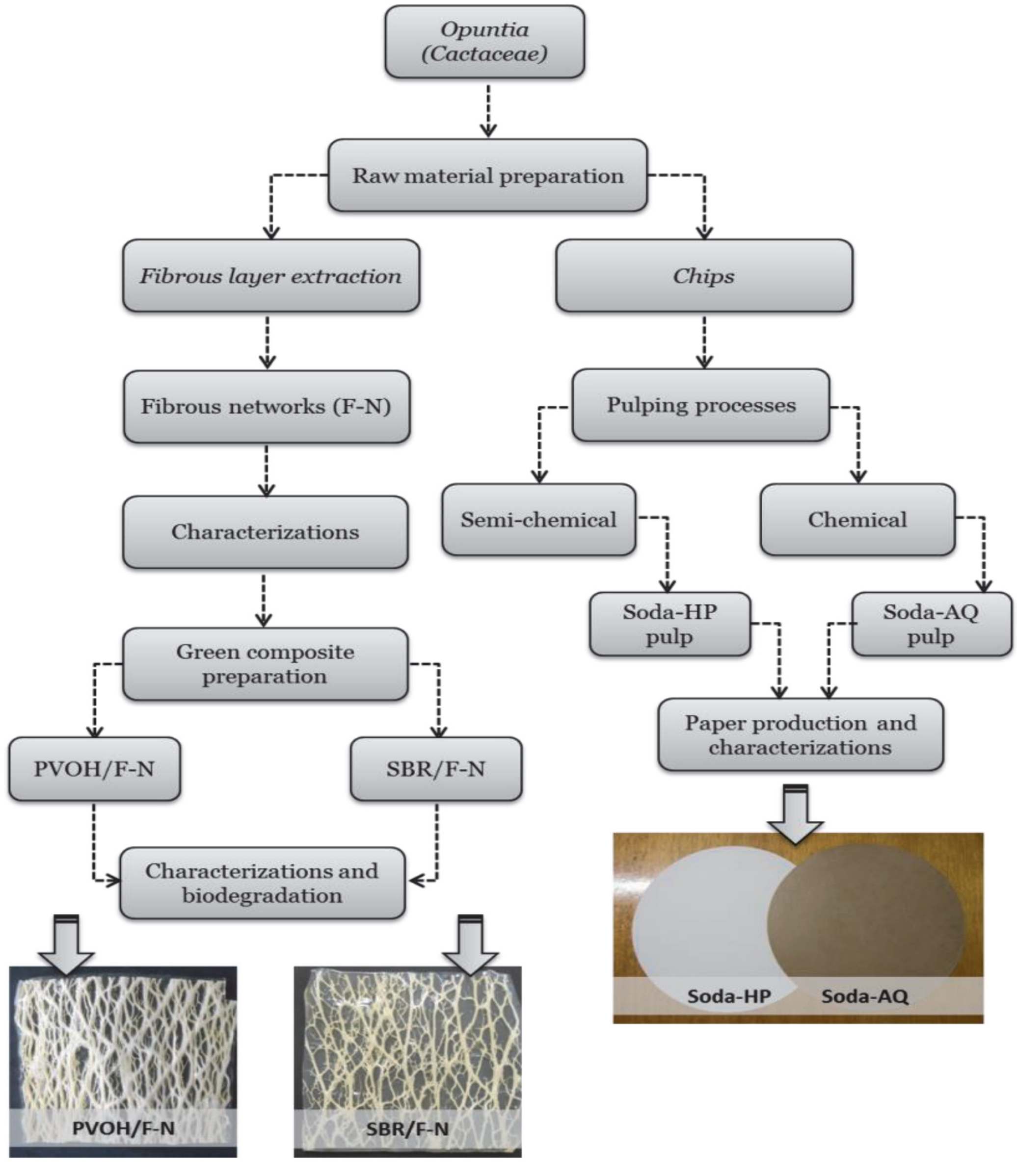

Figure 1.
The flowchart of (i) Opuntia *(Cactaceae) raw material obtained; (ii) pulping and paper manufacturing; and (iii) green composite elaborations.*

matrix structure, and they take loads from the matrix to the fiber in a very easy and effective way [31]. The arrangement and orientation of fibers define the properties and structural behavior of the composite material [32, 33]. *Opuntia* fibers were used as a natural filler to manufacture FRPC such as cactus fiber/polyester [21] and cactus fiber/polylactic acid [34]. This chapter provides an overview of the valorization and of *Opuntia* (Cactaceae) fibers in new green material science such as paper and bio-composite materials using two thermoplastic polymers which are polyvinyl alcohol and styrene butadiene rubber. The valorization ways of *Opuntia* (Cactaceae) fibers have been given in the flowchart in **Figure 1**.

2. Raw material characterizations: *Opuntia* (Cactaceae)

2.1 Fibrous layer extraction and characterizations: morphology, geometric dimensions, and mechanical behaviors

The isolations of fibrous network layers from *Opuntia* (Cactaceae) trunk using a green process in relation to their multifunctional features and its use as a raw material for novel ecological product was hardly studied for the first time by Mannai et al. [9]. **Figure 2** represents the fibrous networks (F-N) extraction steps which was performed manually and subsequently dried at room temperature for 7 days [9]. The obtained F-N layers (about 56 layers) represent a continuous phase (multidirectional fiber orientation angle) obtained from peripheral, middle, and central sections of the trunk, and **Table 1** displays their different characteristics.

Figure 3 shows the microscopic photograph of *Opuntia* fibrous layer obtained from the brightfield microscope. The obtained microscopic views show clearly the presence of axial primary fibers cross-linked by secondary ones. The bifurcation of primary fibers forming an open woven texture with special network design is also worth noting. The dimensions and forms of fibers (primary and secondary) have been related to the distribution of the layers in the trunk.

The F-N properties towards bulk density, morphological parameters including width, angles of opening pores, and area of pores of both fibers (primary and secondary) before and after swelling test, as well as the mechanical properties are listed in **Table 1**.

The peripheral section of the trunk regroups the thicker F-N layers than other sections of the *Opuntia* trunk. The average fiber width increases from the central to peripheral trunk sections and varies proportionally to the thickness of the fibrous layer. The average pore angle increases proportionally with the F-N pore area [9]. The pore angle between the primary fibers for the central section (90°) is 36%

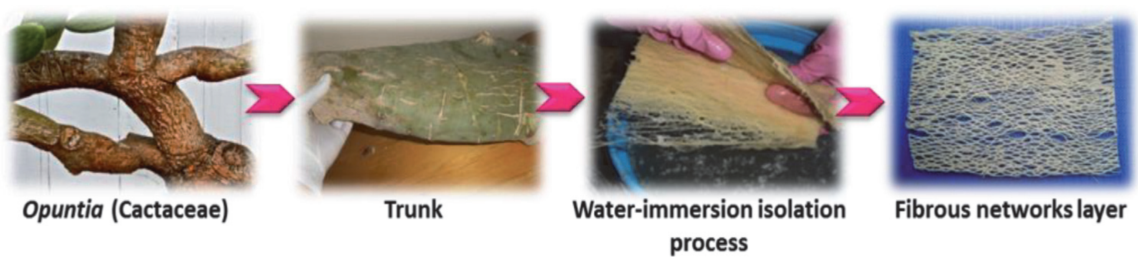

Figure 2.
Water-immersion process for fibrous networks layer extraction from the trunk of Opuntia *(Cactaceae).*

Layer sections	**Peripheral**				**Middle**				**Central**			
Apparent density (kg/m^3)	688–740				486–500				290–320			
Thickness (mm)	2.3–3.75				1.5–2.15				0.41–1.26			
Swelling ratio (%)	180 ± 12				135 ± 3				115 ± 5			
Geometric fiber dimensions	**Primary**		**Secondary**		**Primary**		**Secondary**		**Primary**		**Secondary**	
	Bs	**As**	**Bs**	**As**	**Bs**	**As**	**Bs**	**As**	**Bs**	**As**	**Bs**	**As**
Width (mm)	1.7	3.2	0.64	0.9	1.3	1.25	0.5	0.64	1	1.3	0.4	0.62
Pore angle (°)	54	42	25	20	80.3	68.3	41.1	37	90.7	59	41	26
Pore areas (mm^2)	2.8	1. 2	1.33	0.5	5.74	2.6	0.9	0.45	18.5	8	0.5	0.3
Mechanical structure	**Tensile**		**Flexural**		**Tensile**		**Flexural**		**Tensile**		**Flexural**	
Elastic modulus (GPa)	2.93		2.36		2.11		1.21		1.5		0.99	
Strength (MPa)	14.3		9.7		9.7		8.8		5.2		7.36	
Deformation at break (%)	5.04		6.18		1.7		4		1.4		2.9	

Table 1.
Apparent density, swelling ratio, and their effect on geometric dimensions before swelling (Bs) and after swelling (As) and mechanical strength properties obtained for fibrous networks obtained from peripheral, middle, and central sections of Opuntia *(Cactaceae) trunk.*

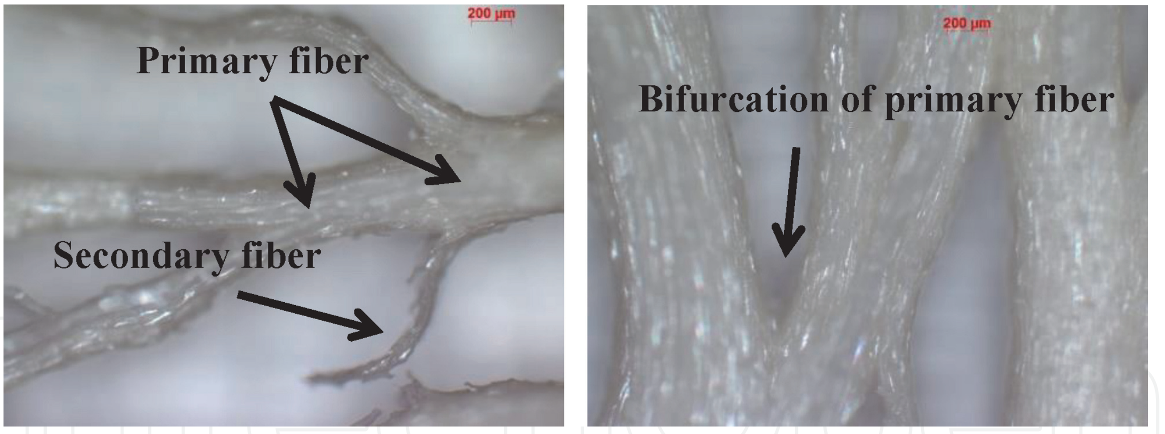

Figure 3.
Microscopic views of the surface of fibrous network layers from Opuntia *(Cactaceae) [200 µm].*

higher than the value obtained for primary fibers studied by Bouakba et al. [21] (about 57.5°); and for the secondary fibers, the pore angle of peripheral section is very acute (25°) compared to the other two sections (**Table 1**). The high obtained width with low pore area and low pore angle size of the outer layers of the trunk (peripheral section) confirm their dense structures which represent important fiber density with low porosity [9]. This finding is confirmed by the measured bulk density of these layers (see **Table 1**). The limited pore of the primary fibers of the central section (18.58 mm^2) was 69% and 84.5% higher than that of the middle and peripheral layers, respectively [9]. It was higher than that of the fibrous layers derived from the *O. ficus-indica* (11.3 mm^2) studied by Bouakba et al. [21].

Otherwise, the swelling ratio and uptakes by peripheral layers are higher than the middle and central ones; this could be due to the internal morphological aspect of *Opuntia* fibers which represent a porous structure, the presence of large fibro-vascular vessels [9, 25], and the high fiber density compared to those of the middle and central sections. The swelling of fibers can be explained by the hydrophilic nature of the Cactaceae plant, which can store a large amount of water [9]. Generally, the fiber hydration is noticed to be linked to the chemical composition of the fibers which have polar hydroxyl sites in their internal structures, which can form hydrogen bonds with water molecules [9]. The water-immersion process (applied for F-N extractions) could eliminate most of the water-soluble compounds (inorganic salts, ashes, coloring matter, etc.) from the fiber structure and favor the creation of void spaces, which could also explain the swelling of the fibers [9, 35].

The fiber water absorption can affect the geometric dimensions of *Opuntia* fibers by increasing the fiber width of both primary and secondary fibers (growth in size of the hydrated fibers) which can cause the decreasing of the pore areas and angles located between the primary and secondary fibers which may be explained by the occupation of the empty surfaces by the swelled fibers. Generally, highly hydrated fibers are characterized by their flexibility and ability to conform to fabric types [9].

The mechanical tensile and flexural behaviors of Cactaceae F-N were summarized in **Table 1**. It was found that the F-N tensile modulus increased from the central to the peripheral layers. The peripheral sections' tensile Young's modulus, uniaxial tensile strength, and deformation at breaks were found to increase compared to those obtained for the middle and central layers [9]. It is noted here that the peripheral layers have a favorably high Young's modulus compared to those of other cactus fibers [33–37].

The different flexural behaviors significantly increase from the central fiber layer to those of the peripheral F-N. This increase can be explained by the variation in geometric shape, layer thicknesses, fiber width, pore area distributions, fiber density, and bifurcation of primary fibers. It is worth noting that the flexural properties measured from the peripheral F-N layers are higher than those *O. ficus-indica* studied by Greco and Maffezzoli [34] and are lower than those found for *Myrtillocactus geometrizans* studied by Schwager et al. [36]. As expected, the F-N structural and geometric aspects modify the tensile and flexural states in such a way that the maximum elastic modulus shifts in an axial direction. This shift can be explained by the primary fiber orientation, which is axially aligned in most of the regions in the direction of the principal stresses and primary fiber density, on a macroscopic level. Mannai et al. [9] and El Oudiani et al. [38] affirmed and confirmed that the major factors that influence the F-N tenacity and elongation and give good mechanical properties include (i) the hierarchical structure; (ii) the unit cell dimensions (large and thick-wall parenchyma cells, long fiber bundles, and the densely distributed periderm with thick cell edges); and, on a microscopic level, (iii) the degree of crystallinity and (iv) the chemical composition of the fibers.

2.2 Chemical composition

Mannai et al. [25, 26] are the first ones to have studied the chemical composition of lignocellulosic fibers from *Opuntia* (Cactaceae) trunk. For comparison purposes, the results of this and other chemical compositions of *Opuntia* cladode studied by Malainine et al. [39] and some lignocellulosic raw materials from plant biomass collected from literature were summarized in **Table 2**.

A lower content of Klason lignin was observed in the *Opuntia* trunk and cladode and does not exceed 5 wt% (as opposed to other plants), indicating that *Opuntia* genus was a non-woody plant. The total holocellulose contents (64 wt%) were

Plant	Ash	K. lig	Holocel	α-cell
Opuntia (Cactaceae) trunk [25]	5.5	4.8	64.5	53.6
Opuntia (Cactaceae) cladode [39]	19.6	3.6	—	21.6
Date palm rachis [40]	5	27.2	74.8	45
Carrot leaves [41]	—	18.51	52.8	31.5
Rapeseed straw [42]	3.4	16	78.9	41.6
Amaranth [43]	12	13.2	58.4	32
Olive trimmings [44]	1	18.9	64.7	59
Softwood [45]	—	25–31	65–74	40–45
Harwood [45]	—	16–24	67–82	43–47
Alfa [46]	3.7	22.3	68.2	46.1
Eucalyptus citriodora [47]	0.8	22.7	—	48.2
Posidonia oceanica balls [40]	12	29.8	61.8	40
Vine stem [48]	3.9	28.1	65.4	35
Banana stem [49]	7.1	11.1	43.60	—
Annual plants [50, 51]	2–6.2	17–26	52–70	36–46

Table 2.
Chemical composition (ash; K. lig, Klason lignin; Holocel, holocellulose; and α-cell, α-cellulose) of Opuntia *(Cactaceae) trunk and other values obtained for cladode and their comparison with several lignocellulosic plants (w/w%).*

similar to that found in *olive trimmings*, hardwood, softwood, vine stems, and some annual plants; and it was clearly higher than those obtained for carrot leaves, amaranth, banana stems, and *Posidonia oceanica* balls; but it was lower than the holocellulose content measured for date palm rachis, rapeseed straw, and Alfa stems. In general, the holocellulose content can provide information about the quality and quantity of the produced pulp and paper [52]. The measured α-cellulose rate was surprisingly higher in the trunk (around 53.6 wt%) than those obtained for cladode (21.6 wt%) and other plants (**Table 2**); it was slightly lower than in *olive trimmings*. Non-wood fibers are handled in ways specific to their composition, and it was also acceptable for papermaking applications and corresponded to paper with enhanced strength [22]. For this reason, the processes used for the delignification of lignocellulosic fibers from *Opuntia* were adapted in very soft conditions to minimize degradation of the fibers and thus maximize pulp yield.

A very small fraction of inorganic compound (5.5 wt%) was observed in the trunk compared to the total mineral amount in the cladode, *Posidonia oceanica balls*, and banana stems; however, it was comparable to the values estimated for date palm rachis; but it was significantly higher than the ash contents measured for rapeseed straw, *olive trimmings*, Alfa stems, *Eucalyptus citriodora* and vine stems, and some annual plants (**Table 3**). The lower fraction of minerals in lignocellulosic fibers from the *Opuntia* trunk presents a major advantage, and the utilized raw material was silica free, which was extremely important for papermaking [25]. The chemical composition of ash was determined with elemental analysis and reported for the first time by Mannai et al. [25]. The resulting proportions, as seen in **Table 3**, are compared with other plants (amaranth, *Astragalus armatus*, date palm rachis, and banana pseudo stems) and have shown that the elemental composition of mineral contents in *Opuntia* can vary considerably from one species to another. A very low fraction of silicon (0.2 wt%) observed for *Opuntia* than those of other raw materials led to good separation after chemical delignification. It is clear that calcium and magnesium are the predominant inorganic materials in the Cactaceae family (18.33 and 16.54 wt%). The high presence of calcium due to the calcium oxalate crystals present naturally in *Opuntia* species [9, 25, 26]. The mineral elements present in this raw material do not present any counterindication for chemical pulping, composite manufacturing, and the area of the extraction of various cellulosic derivatives.

(%)	***Opuntia* (Cactaceae) [25]**	**Amaranth [43]**	***Astragalus armatus* [53]**	**Date palm rachis [40]**	**Banana pseudo stems [49]**
Si	0.2	0.25	18.42	2.8	2.7
Ca	18.33	4.17	11	21.5	7.5
Mg	16.54	0.035	2.90	3.53	4.3
Fe	399 ppm	—	0.29	240 ppm	—
Cu	192 ppm	0.01	˂0.1	360 ppm	—
K	11.1	36.67	0.59	10.2	33.4
P	0.24	—	8.11	0.7	2.2
S	2.51	—	0.94	1.69	—
C	3.84	—	4.1	1.5	—
Na	0.6	—	1.8	6.79	—

Table 3.
Ash composition of Opuntia *(Cactaceae) trunk in comparison with data from previously published studies.*

3. Potential applications of cellulose fibers from *Opuntia* (Cactaceae)

3.1 Pulping and paper manufacturing

For papermaking, two main steps are followed in which the raw material is firstly cooked to obtain fibrous mass (pulp), and then the pulp is converted into paper. Mannai et al. [25, 26] were the first to find the preparation of pulp and papers from *Opuntia* trunk using semi-chemical and chemical pulping procedures, with yields of 80.8 and 41.1%, respectively [54]. Multistep pulping processes were followed to produce pulps and papers from *Opuntia* as shown in **Figure 1**. The manufacturing of pulp starts with raw material preparation [55], in which the dried *Opuntia* trunk was cut into chips (2–3 × 1–2 × 1.5–2 cm^3) [25, 26]. Two processes have already been applied to the delignification of *Opuntia* chips. The semi-chemical procedure based on the chemical treatment of raw material using soda–hydrogen peroxide (soda–HP) mixture (with the control of pH∼11) and the delignification reaction steps are done under reflux [25, 54]; these steps are followed by mechanical deliberation operation of cooked chips to more individualize and deliberate the fibrous suspensions. The obtained soda–HP pulp was purified by the classification of fibers by applying the standard T275 sp-12 method. Likewise, it has already been applied to the delignification of *Opuntia* trunk chips in a procedure described by Mannai et al. [26, 54], which utilized a total soda alkali charge of 20% (w/w o.d.) and an anthraquinone concentration of 0.1% (w/w o.d.). The liquor to solid ratio was kept at 10, and the mixture was cooked for 120 min at 170°C with a temperature ramping rate equal to 2.4°C/min. All of their experiments were conducted in a 1 L reactor that took 1 h to reach a constant temperature.

The morphological fiber’s dimensions of the obtained fibrous suspensions in terms of their average length (mm) and width (μm) and the percentage of fine elements were examined using a MORFI (LB-01) analyzer developed by Techpap. The obtained results are summarized in **Table 4**. The fiber length (and width) of the *Opuntia* semi-chemical and chemical pulps were 764 μm (38 μm) and 737 μm (54.6 μm), respectively, which are in the same range of hardwood fibers [56]. The

Pulp and paper properties	**Pulping process**	
	Semi-chemical [25]	**Chemical** [26]
Yield (%)	80.8	41.4
Fiber length (μm)	764	737
Fiber width (μm)	38	45.6
Fine elements (%)	16.3	29.3
Bases weight (g/m^2)	38.4	65.2
Thickness (μm)	149	135
Bulk (cm^3/g)	2.26	2.07
Burst index (kPa m^2 g^{-1})	0.67	5.8
Tear index (mNm^2 g^{-1})	19.2	12
Young’s modulus (GPa)	1.7	1.83
Breaking length (km)	1.9	1.57

Table 4.
Fiber and handmade paper produced from Opuntia *(Cactaceae) pulps after semi-chemical and chemical pulping procedures.*

processing with semi-chemical procedure gives a thick individualized fiber. It was considered as short fiber species [54]. It is also necessary to note that the pulp obtained from chemical procedures (at high temperature ∼170°C) was characterized by a high content (29.3% of the length) of fine elements.

The semi-chemical and chemicals pulps obtained from *Opuntia* trunk after delignification were exploited to make hand sheets. Paper sheets have been successfully manufactured as shown in **Figure 1**. Papers from semi-chemical pulps are the whitish than the ones obtained from chemical pulp. This is explained by the treatment with hydrogen peroxide which oxidizes the color of chemical groups.

The given data of physical properties of hand sheet papers, as seen in **Table 4**, confirms that the studied raw material has potential for use in paper manufacturing using the soft delignification by applying the semi-chemical procedure which can affect the paper properties by increasing the fiber flexibility and strength [22, 25, 54]. Thus, these data suggest that *Opuntia* (Cactaceae) fibers can be used for producing paper from non-woody plants with various qualities (strength) and for future green product applications.

3.2 *Opuntia* (Cactaceae) fibrous network (F-N)-reinforced polymer composites: PVOH/F-N and SBR/F-N

The reinforcing potential of F-N obtained from *Opuntia* (Cactaceae) trunk was also investigated by Mannai et al. [57], and the flowchart in **Figure 1** shows the main manufacture steps. Composites filled with F-N from *Opuntia* (Cactaceae) seem to be promising materials for green applications. Natural plant fiber polymer composites are a composite material consisting of a polymer matrix embedded with natural fibers [58]. It is representing a promising domain of value-added products derived from low-cost and naturally occurring raw materials. The processing methods performed to synthesize bio-composites are mainly based on fiber type, form, and position. *Opuntia* F-N was used as a bidirectional filler with intricate structure; it is considered as a heterogeneous sheet filler. Two thermoplastic polymers, which were polyvinyl alcohol (PVOH) and styrene-butadiene rubber (SBR), were used as the matrix polymers. The hand lay-up molding processing of PVOH and SBR-based composites was chosen according to the networks form of fibrous layer of *Opuntia*. The reinforcing potential of fibrous networks in composites was investigated by evaluating their properties, and interfacial adhesions between polymer/fibers were studied. The major factor that affects the reinforcement composite properties is the bonding strength between fiber and polymer matrix in the composite.

The previous sections have provided some characters of *Opuntia* (F-N)-reinforced polymer composites obtained from dynamic mechanical analysis (DMA), thermogravimetric analyses (TGA), and biodegradation potential (BP). DMA was carried out by testing strips in axial (VF) and horizontal (HF) directions of incorporated fibers in order to understand the effect of additives and fillers on composites or filled materials [59]. As given in the previous work reported by Mannai et al. [57], the incorporation of fibers vertically for each matrix enhanced the storage modulus, especially for SBR-based composite. Otherwise, the relaxation process for composites reinforced with fibers oriented vertically is significantly higher than the one obtained for the filler oriented horizontally [57]; this can be explained by the elastic behavior of thicker axial fibers than other fibers interconnected with bifurcation ones [9] (see **Figure 3**). Mechanical interlocking and interfacial bonding adhesion are sensitive and can be improved by the natural fibers' surface roughness (**Figure 3**). The thermal behavior of *Opuntia* (F-N)-reinforced polymer composites was carried out using TGA in the conditions described in detail by Mannai et al. [57]. The main thermal data are summarized in

Composites	T (°C)	Discussion
PVOH/F-N [57]	30–120	Evaporation of residual moisture
	120–380	Degradation of hemicelluloses in lignocellulosic fibers and the elimination of hydroxide groups from PVOH in the form of water molecules
	380–520	Decomposition of chain segments of PVOH molecules and lignocellulosic compounds (cellulose and lignin)
SBR/F-N [57]	30–300	Evaporation of absorbed moisture and residual water in SBR latex
	300–570	Volatilization of SBR (styrene derivative) and lignocellulosic fibers (cellulose and lignin)

Table 5.
Thermal characteristics of PVOH and SBR-based composites reinforced with F-N layers of Opuntia *(Cactaceae) trunk obtained from TGA measurements.*

Table 5. From the discussion in **Table 5**, we can notice that F-N enhances the thermal properties of the used thermoplastic polymers.

The biodegradability potential (BP) (soil-burial test) of the matrix and produced composites were obtained by the mass retention technique, following the procedure outlined in literature [60, 61], and the results are given in the previous work [57]. The evolution of BP vs. time for the different materials after soil burial decreases gradually and tends to 93 and 86.6%, respectively, for PVOH/F-N and SBR/F-N [57]. These values are higher than those reported for PVOH/palm kernel shell powder bio-composites (20%) [62] and PVOH/corn starch films (40%) [63]. It should be mentioned that cellulosic fibers from *Opuntia* (Cactaceae) plant, PVOH, and SBR are biodegradable in nature, in which they may serve as a source of energy and carbon for specific microorganisms [64, 65]. From this study, eco-friendly *Opuntia*-derived fiber-reinforced polymer (thermoplastic) composites would be the materials for near future not only as a solution to the growing environmental threat but also as a solution to alleviating the uncertainty of the petroleum supply.

4. Conclusions

Opuntia (Cactaceae) is an alternative and sustainable plant for fiber production for semiarid and arid regions. It is in large quantities and considered as a useful source in most countries without forests. Indeed, natural fibers derived from Tunisian *Opuntia* (Cactaceae) plants prove their greatest potentials for use in paper manufacturing by applying two pulping processes which affects the pulp properties and paper characteristics and composite applications (as reinforcement in thermoplastic polymers) because of their excellent characteristics such as low density, high specific stiffness, good mechanical properties, biodegradability, eco-friendliness, and good thermal resistance. *Opuntia* fibers can be a good reinforcement candidate for high-performance biodegradable polymer composites. This study has paved the way of proposing this xerophyte genus as a suitable new resource of non-woody fibers at different fields and as an environmentally friendly alternative to green product.

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Conflict of interest

The authors declare no conflict of interest.

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